

STUDY OF POLARIZATION OF LIGHT  
SCATTERED BY SEA WATER

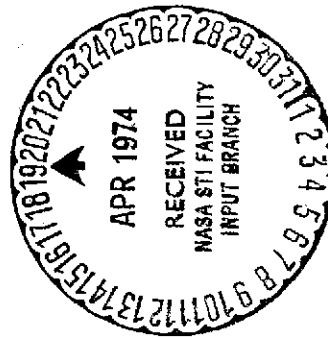
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# STUDY OF POLARIZATION OF LIGHT SCATTERED BY SEA WATER

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The Stokes parameters determine the state of a light beam, /136\* which may be written as follows [1]

$$S_1=I; S_2=IP\cos 2\Psi; S_3=IP\sin 2\Psi; S_4=Iq;$$

where  $I$  is the intensity (brightness) of the light beam;  $P$  — light beam degree of polarization;  $\Psi$  — angle of rotation of the direction of the "maximum" polarization with respect to the scattering plane;  $q$  — degree of ellipticity.

An arbitrary, partially polarized light beam with the intensity  $I$  may be represented as the sum of two incoherent beams: a completely polarized beam with the intensity  $I' = rI$  and a completely depolarized beam with the intensity  $I'' = (1 - r)I$ . The quantity  $r = +\sqrt{P^2 + q^2}$  is the light beam degree of uniformity.

The scattering matrix, which is the linear operator of the transformation of Stokes parameters in the case of scattering of light by sea water, was experimentally determined by a laboratory /137 matrix measurement.]

The first column of the scattering matrix characterizes the scattering volume of a turbid medium when it is irradiated with a completely depolarized (natural) light with the Stokes parameters

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\*Numbers in the margin indicate pagination of the original foreign text.



$$S_1 = I, S_2 = S_3 = S_4 = 0.$$

The polarization parameters of scattered light, when it is irradiated by natural light, are found from the following formulas:

$$\left. \begin{aligned} P_* &= +\sqrt{\tilde{f}_{21}^2 + \tilde{f}_{31}^2}; \\ \Psi_* &= \pm \left| \frac{1}{2} \operatorname{arctg}(\tilde{f}_{31}/\tilde{f}_{21}) \right| \text{ for } \tilde{f}_{21} > 0; \\ \Psi_* &= \pm \left[ \frac{\pi}{2} - \left| \frac{1}{2} \operatorname{arctg} \frac{\tilde{f}_{31}}{\tilde{f}_{21}} \right| \right] \text{ for } \tilde{f}_{21} < 0; \\ q_* &= \tilde{f}_{41}; \\ r_* &= +\sqrt{\tilde{f}_{21}^2 + \tilde{f}_{31}^2 + \tilde{f}_{41}^2}. \end{aligned} \right\} \quad (1)$$

In the formulas for  $\Psi_*$ , the sign (+) appears when  $\tilde{f}_{31} > 0$ , and the sign (-) — when  $\tilde{f}_{31} < 0$ . If  $\tilde{f}_{31} = 0$ , then when  $\tilde{f}_{21} > 0$  the angle  $\Psi_* = 0$ , and when  $\tilde{f}_{21} < 0$  the angle  $\Psi_* = \pi/2$ . If  $\tilde{f}_{21} = 0$ , then when  $\tilde{f}_{31} > 0$  the angle  $\Psi_* = +45^\circ$ , and when  $\tilde{f}_{31} < 0$ , the angle  $\Psi_* = -45^\circ$ .

The second column of the scattering matrix characterizes the scattering volume of a turbid medium when it is irradiated by linearly polarized light beams: beams which are horizontally polarized  $\{S_1 = S_2; S_3 = S_4 = 0\}$  and beams which are vertically polarized  $\{S_1 = -S_2; S_3 = S_4 = 0\}$ .

The third column of the scattering matrix characterizes the scattering volume when it is irradiated by linearly polarized light beams with the polarization angles  $\Psi = \pm 45^\circ \{S_1 = S_3; S_2 = S_4 = 0\}$ ,  $\{S_1 = -S_3; S_2 = S_4 = 0\}$ .



The fourth column of the scattering matrix characterizes the scattering volume when it is irradiated by light beams with circular polarization  $\{S_1 = S_4; S_2 = S_3 = 0\}$ ,  $\{S_1 = -S_4; S_2 = S_3 = 0\}$ .

The polarization parameters of the scattered light, when it /138 is irradiated by completely polarized light beams, may be found from the following formulas

$$\left. \begin{aligned} \rho_j^\pm &= \pm \frac{\sqrt{(\tilde{f}_{21} \pm \tilde{f}_{2j})^2 + (\tilde{f}_{31} \pm \tilde{f}_{3j})^2}}{1 \pm \tilde{f}_{1j}}; \\ \Psi_j^\pm &= \pm \left| \frac{1}{2} \operatorname{arctg} \left\{ \frac{\tilde{f}_{31} \pm \tilde{f}_{3j}}{\tilde{f}_{21} \pm \tilde{f}_{2j}} \right\} \right|, \text{ for } (\tilde{f}_{21} \pm \tilde{f}_{2j}) > 0; \\ \Psi_j^\pm &= \pm \left[ \frac{\pi}{2} - \left| \frac{1}{2} \operatorname{arctg} \left\{ \frac{\tilde{f}_{31} \pm \tilde{f}_{3j}}{\tilde{f}_{21} \pm \tilde{f}_{2j}} \right\} \right| \right], \text{ for } (\tilde{f}_{21} \pm \tilde{f}_{2j}) < 0; \\ q_j^\pm &= \frac{\tilde{f}_{41} \pm \tilde{f}_{4j}}{1 \pm \tilde{f}_{1j}}; \\ r_j^\pm &= \pm \frac{\sqrt{(\tilde{f}_{21} \pm \tilde{f}_{2j})^2 + (\tilde{f}_{31} \pm \tilde{f}_{3j})^2 + (\tilde{f}_{41} \pm \tilde{f}_{4j})^2}}{1 \pm \tilde{f}_{1j}}. \end{aligned} \right\} \quad (2)$$

The signs ( $\pm$ ) in the case of the polarization parameters correspond to the irradiating beams with  $\{\pm S_j\}$ , where  $j = 2, 3, 4$ .

In the formulas for  $\Psi_j$ , the sign (+) appears when  $\tilde{f}_{31} \pm \tilde{f}_{3j} > 0$ , and (-) — when  $(\tilde{f}_{31} \pm \tilde{f}_{3j}) < 0$ . If  $(\tilde{f}_{31} \pm \tilde{f}_{3j}) = 0$ , then when  $(\tilde{f}_{21} \pm \tilde{f}_{2j}) > 0$  the angle  $\Psi = 0$ , and when  $(\tilde{f}_{21} \pm \tilde{f}_{2j}) < 0$   $\Psi_j = \pi/2$ . If  $(\tilde{f}_{21} \pm \tilde{f}_{2j}) = 0$ , then when  $(\tilde{f}_{31} \pm \tilde{f}_{3j}) > 0$  the angle  $\Psi_j = +45^\circ$ , and when  $(\tilde{f}_{31} \pm \tilde{f}_{3j}) < 0$   $\Psi_j = -45^\circ$ .



In (1) and (2) the terms  $\tilde{f}_{ij}$  are the relative components of the scattering matrix [1].

The components of the scattering matrix for sea water obtained experimentally have a smoother form than for mono-dispersed latex. The angular dependences of the scattering matrix components are more sensitive functions than the scattering indicatrices. Some of the scattering matrix components shown in Figure 1 correspond to two samples of sea water with similar scattering indices. The samples were obtained in the northeastern part of the Black Sea in December of 1969, 1.5 miles from the shore at a depth of ten meters. The table gives the data from membrane filtration in percent,

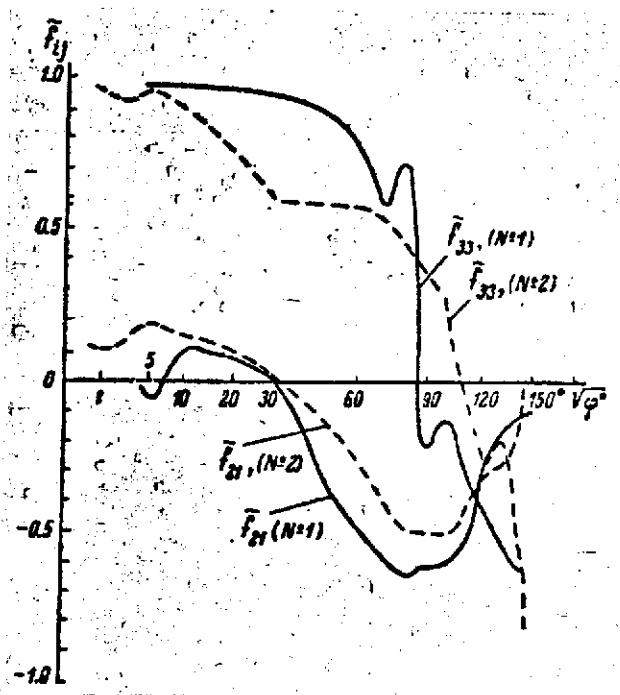


Figure 1. Relative components of the scattering matrix for samples No. 1 and No. 2.



| Number of sample,<br>characteristics                                 | Particle diameter, $\mu\text{m}$ |       |      |       |       |     | Total<br>number<br>of<br>particles<br>$\text{m}^{-3}$ | Suspended<br>matter<br>$\text{g}/\text{m}^3$ |
|--|----------------------------------|-------|------|-------|-------|-----|---|--|
|  | 1-2.5                            | 2.5-5 | 5-10 | 10-25 | 25-50 | >50 |   |  |
| № 1<br>$\sigma = 0.047 \text{ m}^{-1}$<br>$s = 0.076 \text{ m}^{-1}$ | 70.5                             | 7.3   | 7.1  | 11.5  | 3.5   | 0.1 | $873 \cdot 10^6$                                      | 0.62   |
| № 2<br>$\sigma = 0.051 \text{ m}^{-1}$<br>$s = 0.09 \text{ m}^{-1}$  | 71.0                             | 8.4   | 7.6  | 10.5  | 2.0   | 0.5 | $911 \cdot 10^6$                                      | 0.71   |

The theoretical scattering indicatrix of spherical particles for a certain distribution of particles by size similar to the Young distribution [2] closely coincides with the experimental values, if it is assumed that scattering at angles greater than  $15^\circ$  is determined by particles with  $\rho \leq 6$  and the refractive index /139  $n = 1.15 - 1.20$ . At small angles, the scattering is determined by the particles with  $\rho > 6$  and with the refractive index  $n = 1.05$ . Assuming that the particles are spheres, according to K. S. Shifrin [3], we may establish that all of the light which is refracted twice is located within a cone with the angle of opening of about  $20^\circ$  for  $n = 1.05$ . Since up to 50 — 90% of the small particles which cannot be collected by geologists are found in sea water, all the characteristics in the polarization curves at scattering angles greater than  $15 - 20^\circ$  depend on particles with  $\rho \leq 6$ , which correspond in scattering theory to an intermediate case between Rayleigh scattering and geometric /140 optics. At scattering angles up to  $15 - 20^\circ$ , the basic polarization phenomena will be produced by large particles with optical properties which differ very little from the optical properties of sea water.



*Scattering of circularly polarized light (Figures 2, 3, 4).*

Within an accuracy of a constant factor, the component of the scattering matrix  $f_{14}$  equals the difference between intensities of scattered light and clockwise-polarized light and counter-clockwise-polarized light. Based on the curve of  $f_{14}$  for sample No. 1, we can see that the values of  $f_{14}$  are positive at angles of about  $6^\circ$ , although their values are small. Within the accuracy of experimental error, in the remaining interval of angles  $f_{14}$  may be assumed to equal zero, with the exception of the angles  $40 - 80^\circ$ , where these values are negative (reaching  $-0.2$ ).

For sample No. 2, the value of the component  $\tilde{f}_{14}$  everywhere may be assumed to equal zero with the exception of angles from  $130^\circ$ , where the value of  $f_{14}$  is negative.

The curves of  $q_4$  for both samples are very similar to each other, with a certain shift of the local maxima for sample No. 1 to larger scattering angles. It is not possible to give any quantitative characteristics. In the case of scattering of clockwise-polarized light, the ellipticity disappears for both samples at scattering angles of  $100^\circ$ .

The fact that the curves  $q_4^\pm$  behave differently in the region of angles  $90^\circ$  may be explained by the anisotropy of the optical properties of the material of the scattering centers. The larger anisotropy is observed for sample No. 1.

Samples Nos. 1 and 2 differ very greatly in terms of the degree of linear polarization  $P_4^\pm(\varphi)$ . The greatest divergence between  $P_4^+$  and  $P_4^-$  is observed for sample No. 2. For example, for the angle  $70^\circ$   $R^- \approx 0$ , and  $R^+ = 0.8$  — this value is a maximum value.



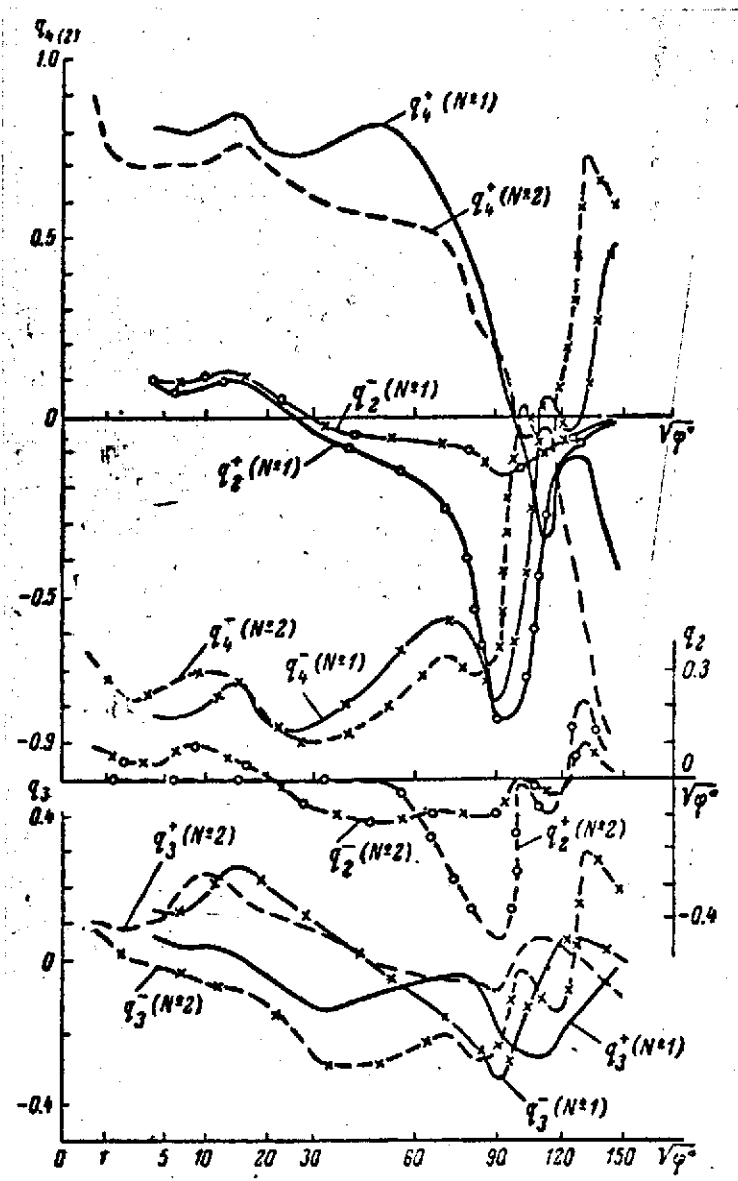


Figure 2. Ellipticity of the scattered light from alternately polarized irradiating light beams.

(No. 1), (No. 2) — number of samples in all the figures.



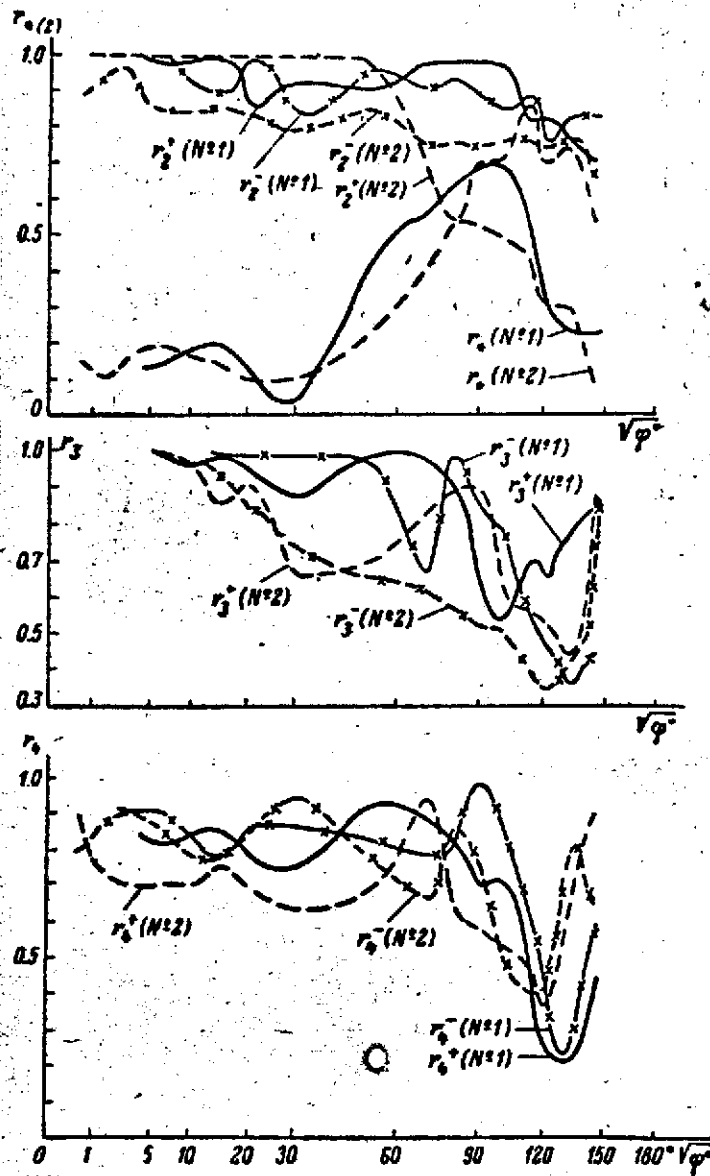


Figure 3. Degree of uniformity of scattered light from alternately polarized irradiating light beams.



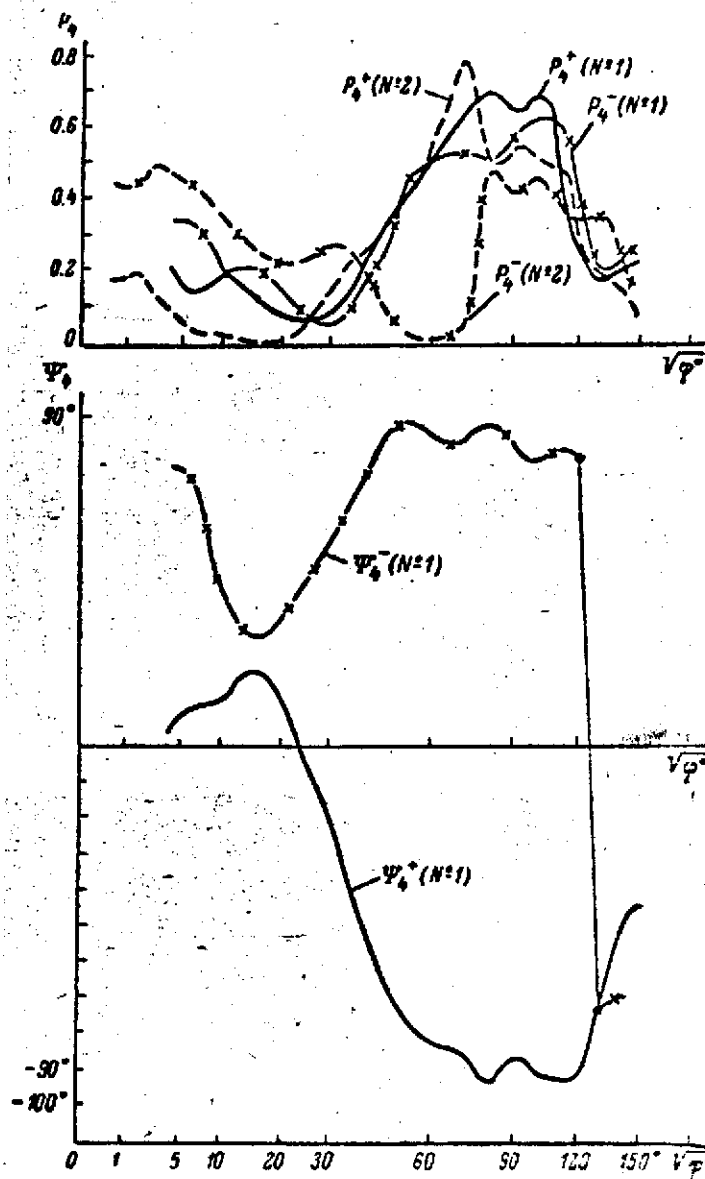


Figure 4. Degree of polarization  $P$  and angle of polarization  $\Psi$  of scattered light from alternately circular-polarized irradiating light beams.

For sample No. 2: from 0.5 to 10 and from 20 to 130°  $\Psi_4^+ = \pi/2$ ; at  $\varphi = 15$  and 145°,  $\Psi_4^+ = 0$ ; from 0.5 to 50  $\Psi_4^- = 0$ ; from 70 to 145°  $\Psi_4^- = \pi/2$ .



The depolarization properties of a scattering volume determine the form of the curve  $r_4(\varphi)$ . The curves display a certain pattern. Since curve  $r_4$  characterizes the polydispersity of the scattering volume, we may conclude that sample No. 2 is more polydispersed, but the largest minimum is characteristic for sample No. 1 at a scattering angle of  $130^\circ$ .

*Scattering of alternately polarized light beams with the polarization angle  $\pm 45^\circ$  (Figures 2, 3, 5).* Within an accuracy of a constant factor, the behavior of the component of the scattering matrix  $f_{13}$  equals the difference between the total intensities of scattered light beams and linearly polarized irradiating light beams with the polarization angle  $\pm 45^\circ$ . The value is small for sample No. 1, and vanishingly small for sample No. 2. /144

The ellipticity for both samples does not exceed 0.35 anywhere. The behavior of the curves  $q_3^+$  and  $q_3^-$  is approximately the same as with the parallel shift of one curve with respect to the other and small deformation. The small values of  $q$  in the entire range of scattering angles provide a basis for assuming that the suspended matter material is a dielectric with very small losses. The uniformity of the scattered light  $r_3(\varphi)$  is greater for sample No. 1. The angular behavior of the curve for the polarization angle provides a basis for assuming a greater uniformity in the forms of the scattering centers, however with great deviations from a spherical form. Greater uniformity with small  $\rho$  characterizes sample No. 1. /145



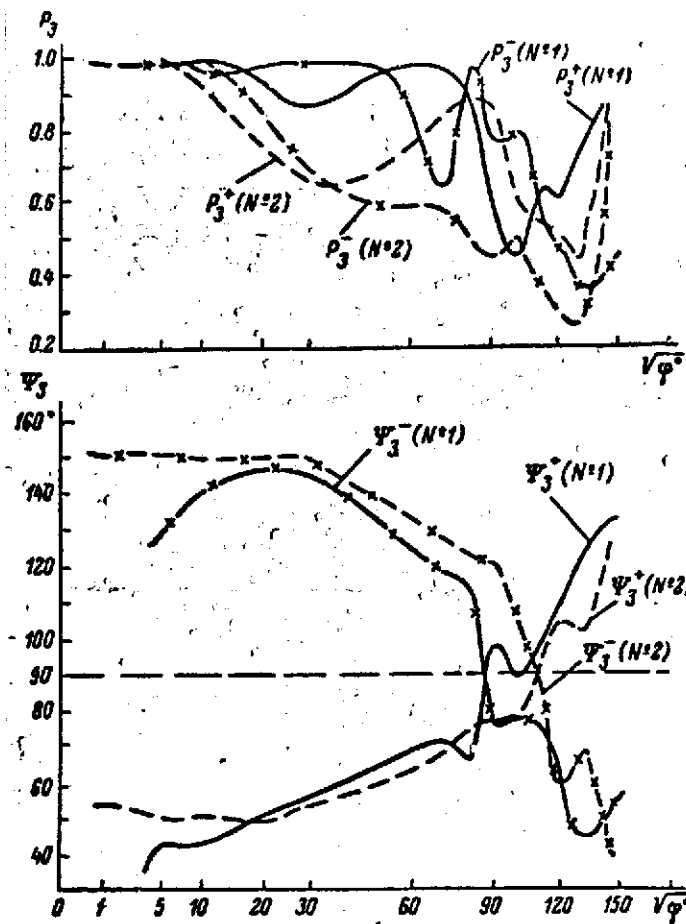


Figure 5. Degree of polarization  $P$  and angle of polarization  $\Psi$  of scattered light from irradiating light beams which were alternately linearly-polarized at an angle of  $\pm 45^\circ$ .

*Scattering of horizontally and vertically polarized light beams (Figures 2, 3, 6).* The same statement may be made regarding component  $f_{12}$  as regarding components  $f_{13}$  and  $f_{14}$ . Its behavior is somewhat similar to the behavior for scattering centers in the form of spheres, only with a maximum which is smaller by  $30 - 40^\circ$ . The maximum for sample No. 1 extends from  $80$  to  $110^\circ$ , and for sample No. 2 the maximum occurs at  $\varphi = 100^\circ$ .



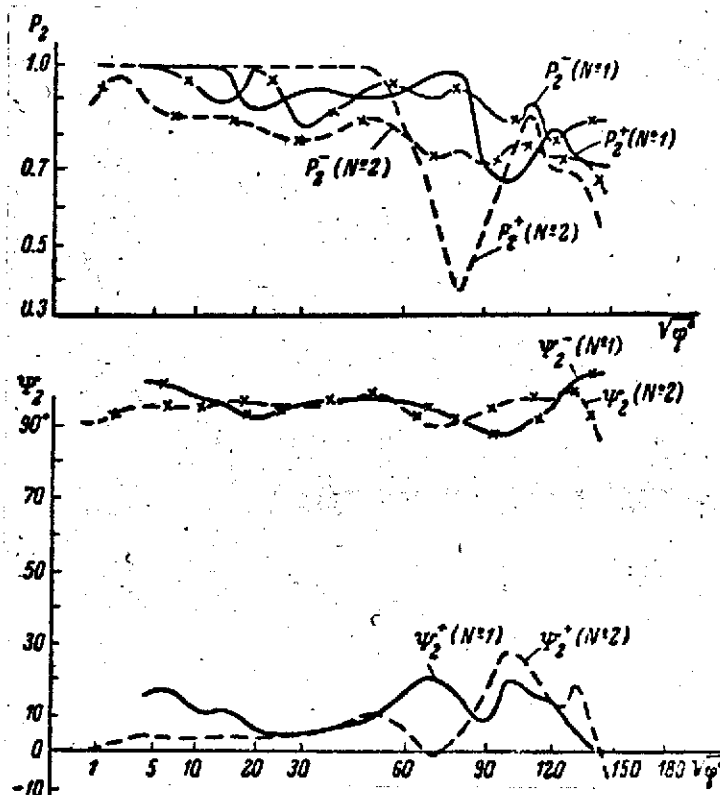


Figure 6. Degree of polarization  $P$  and angle of polarization  $\psi$  of scattered light from irradiating light beams which were horizontally polarized (+) and vertically polarized (-).

With a scattering angle of  $90^\circ$ , the samples for horizontally polarized beams have the greatest ellipticity. For sample No. 1, /146 this ellipticity  $q_2^+$  is very large. In the case of scattering of vertically polarized light beams, the ellipticity for both samples is insignificant in the entire range of scattering angles.

The fact that behavior of  $q_2$  is not identical points to significant anisotropy of the properties of the scattering centers. This anisotropy is higher for sample No. 1.



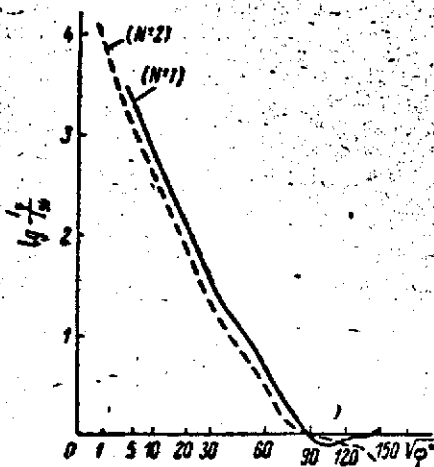


Figure 7. Scattering indicatrices of light for two samples of sea water No. 1 and No. 2 with similar values of the scattering index.

The behavior of the curve for  $r_2$  once more confirms the assumption regarding higher polydispersity of sample No. 2.

*Scattering of natural light* (Figures 3, 7, 8). The component  $f_{11}$  of the scattering matrix, within an accuracy of a constant factor, gives the intensity of scattered light in the case of irradiation of a volume of a turbid medium by natural light. Figure 7 gives the scattering indicatrices for these two samples of water. Many studies

have been devoted to analyzing the suspended matter in terms of the form of the scattering indicatrix. It is everywhere assumed that the suspended matter has a spherical form. Based on the form of the scattering indicatrix, we may select the function for the particle distribution by size. It is impossible to obtain any data on the form, optical properties, anisotropy of scattering particles, and their orientation in space from data on the indicatrix.

In the case of scattering of natural light, insignificant ellipticity appears, which is characteristic for particles having a non-spherical form, or nonuniformity of optical properties of the scattering centers. Within the limits of the experimental error, it may be assumed that the ellipticity is the same for both samples. The degree of linear polarization  $P_*$  for sample No. 2 from 30 to 145° has the polarization angle 90°, and at



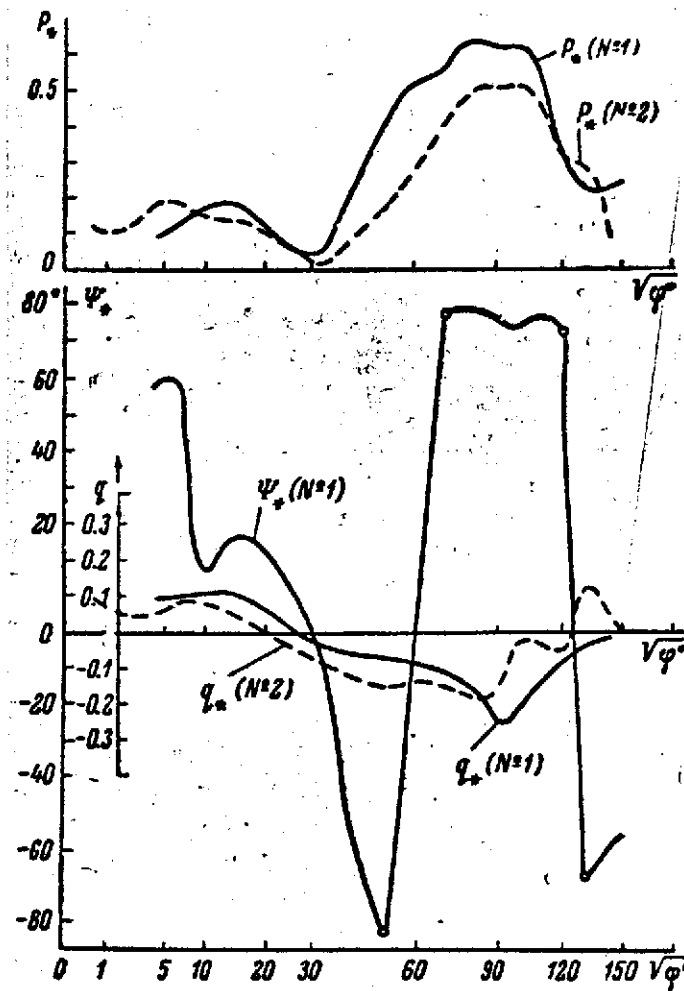


Figure 8. Degree of polarization  $P$  and angle of polarization  $\Psi$  of scattered light from a natural, irradiating light beam.

For sample No. 2: at  $\varphi$  to  $30^\circ$   $\Psi_* = 0$ ; at  $\varphi$  from  $30$  to  $145^\circ$   $\Psi_* = \pi/2$ .

smaller angles this angle equals 0. This degree of polarization points to a divergence from a spherical form of the scattering centers, which is less than for sample No. 1. The spectrum of the dimensions is wider for sample No. 2, which is indicated by the smaller values of the degree of uniformity  $r_*$ .

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The angular dependences of the polarization characteristics of scattered light with similar scattering indicatrices  $\sigma$  point to a difference in the composition of the suspended matter in the samples studied.

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